A robust approach for digital mapping of rock masses with a stereo camera

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ABSTRACT

Digital rock mass mapping has advanced significantly over the last decade, primarily involving the generation of point clouds from exposed rock surfaces. Subsequently, various algorithms have been employed to identify and map the planar segments of these point clouds, representing the surfaces of rock discontinuities. However, this method often overlooks data from the traces of discontinuities that may be present on the exposed rock surfaces. Therefore, utilising stereo cameras could be more effective compared to LiDAR scanning methods for mapping rock masses, as they can capture the rock surface texture (traces of discontinuities on the rock mass exposures) along with the visible planar elements. In this manuscript, we demonstrate a robust mapping algorithm developed for rock mass mapping with a stereo camera, which can be used not only for mapping but also for georeferencing the mapped discontinuities. Furthermore, we provide a demonstrative example where the method is used for rock mass mapping and identifying the rock block size distribution in intact rock.

INTRODUCTION

One of the biggest challenges in mining and rock engineering is the reliably characterisation of rock masses. Traditionally, rock masses are described according to the geometry of their discontinuities which may be measured by scan-lines, scan-windows or oriented boreholes (Priest, 1993). These techniques are time consuming and influenced by the experience and judgment of the geologist conducting it. The mapping outcomes can be used either in rock mass classifications methods to assess the rock mass stability or employed to generate discontinues numerical or analytical calculations. The traditional rock mass mapping becomes more challenging as the size of the projects and geotechnical complexity rises. Furthermore, sometimes safe and accessible zone for a geologist to access and map rock mass is not available. Consequently, the demand for reliable digital tools for rock mass mapping continues to grow.

Digital rock mass mapping techniques can be divided into two categories: traditional point cloud methods that relay on statistical method and geometric constrains; and the powered methods by Artificial Intelligence (AI). AI based approaches are currently less favoured as they typically require large volume of a reliably labelled rock mass training data. However, with utilising the methods which are described for example in this manuscript, it is become possible in the near future to generate standardised labelled databases for training and quantifying the reliability of the AI assisted rock mass mapping methods.

Battulwar *et al* (2021) critically reviewed all available digital rock mass mapping methods that utilises tradition statistical and geometric methods on point clouds describing their advantages and disadvantages. They concluded that among the different methods of digital rock mass mapping the approaches based on voxels growing are superior compared to the others. In the voxel growing method the user or automatically a small area were selected which is planar, and then the size of area grows as the neighbouring area also satisfies the planarity criteria. Similarly, and more recently Yi *et al* (2023) applied advanced data analytics methods to implement voxel growing algorithm over point cloud for mapping planar patches, which shows the method of voxel growing has the potential to be the most reliable and used method in the close future. Hence in this manuscript we also implemented a semi-automated similar approach utilising a stereo camera.

Among the literature reviewed by Battulwar *et al* (2021), they identified that calculating the discontinuity trace length (a measure of discontinuity persistence) utilising Normal tensor voting is a robust method. This approach works only on the meshed surface which is generated from point cloud of the scene. However, such method does not fully consider the three dimensional geometry of the discontinuities.

In conclusion, a robust algorithm for rock mass mapping – considering what an expert geologist might do in the field- should not only map visible planar patches on rock surfaces but also consider discontinuities that lack having visible planar sections in the recorded scene and may have only visible traces. Hence, a robust mapping method should consider both the point cloud and process the images from the rock mass surface to find three-dimensional correspondences on visible discontinuity surfaces. Therefore, this paper demonstrates a method that considers both point cloud data and images from scenes recorded by a stereo camera for comprehensive rock mass mapping. In addition, utilising stereo camera helps us to fuse it with sensor data to automatically georeferenced the mapped scene.

ROCK MASS MAPPING UTILISING STEREO CAMERA

Point cloud is a collection of point coordinates representing surface of a physical object in a specific coordinate system. There are two different techniques for estimating point clouds from images: triangulation (stereo matching) and reconstruction (structure from motion, SFM). In the SFM method both scene geometry (which is called in machine vision terminology as structure) and camera geometry (camera motion) are estimated with a nonlinear optimisation technique (Szeliski, 2011). In SFM method the generated point cloud is not scaled, and we need to know distance between several points within the point cloud to correct the scale.

For the triangulation method, two calibrated cameras are required. Calibrated camera means that we know extrinsic and intrinsic parameters of the camera. Extrinsic properties of the camera define the location and orientation of the camera reference system with respect to a word reference frame (pose of camera in the world coordinate system). Intrinsic properties of the camera link the pixel coordinate of an image with the camera reference frame. Intrinsic properties include focal length, principal point, skew coefficient, and distortion (it shows the radial and tangential distortions in the image). These properties are obtained by mapping several points where their distance from each other is known from forehand. The camera calibration to obtain the intrinsic properties can be done just one time and is not required for the rest of the operation. However, the extrinsic parameters needed to be updated by every frame recorded by the camera. In the stereo matching method two images are used to estimate 3D model (coordinate of points). In this technique the matching pixels of images are find and then the 2D position of them in the images is converted to 3D depth map (like topography map). To make the calculations simpler, two cameras can be parallel with each other while they have only translation type of movement between them. Nowadays there are off-the-shelf stereo cameras with very reasonable price which can be to utilise in digital rock mass mapping. In addition, they might be equipped with Global Navigation Satellite System (GNSS) sensor or Inertia Navigation Systems (INS) which makes estimating of the camera poses per frame quite accurate.

Stereo cameras also provide an ability of storing images from the scene. The images can be used manually by the geologist to quality control the automated mapping results and to perform manual mapping. In this study we are utilising Zed 2i camera from Stereolabs (2023). This stereo camera equipped with its own Software Development Kit (SDK) and an Inertia Measurement Unit (IMU).

Figure 1 presents the algorithm utilised in this study to map rock discontinuities. The movie recorded by the camera is first georeferenced either by using GNSS data from the camera sensor or by using landmark points with known coordinate in the GNSS-denied area (see next section). In addition to mapping the planar patches in the point cloud, discontinuity traces are mapped in the images to identify discontinuities whose surfaces are either not visible for mapping or not captured due to the camera position. After that coplanarity of all the mapped planar elements in the scene are controlled and coplanar elements are merged. Finally, the mapped discontinuities are clustered to obtain their median dip and dip-direction while calculating their normal spacing and rock block size distribution, as denoted as the characterising rock discontinuity network.

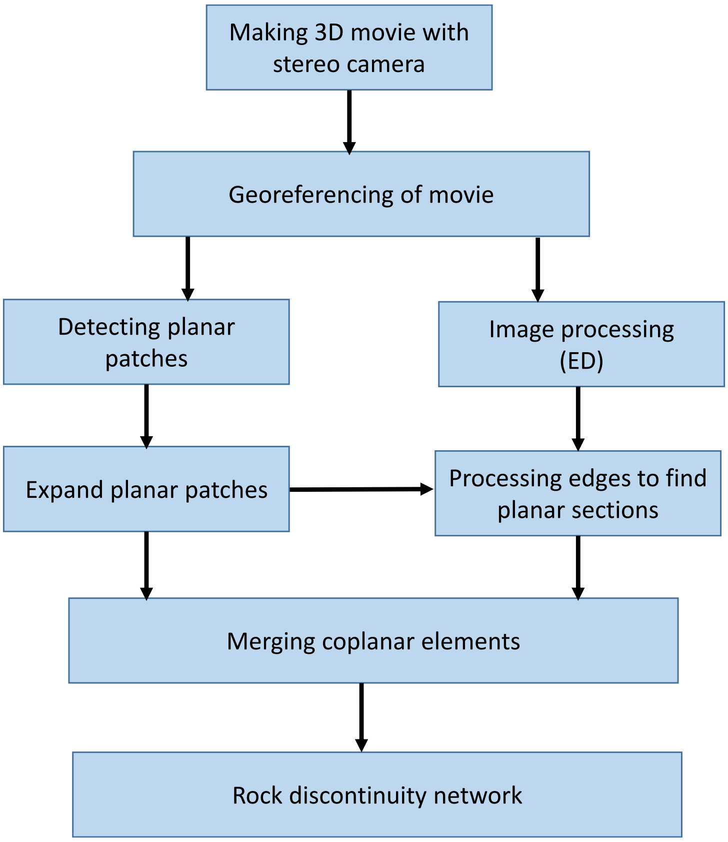

FIG 1 – The algorithm utilised in this manuscript to map rock mass discontinuities with a stereo camera.

Georeferencing

The movies recorded by a stereo camera will be georeferenced to represent the mapped geometry of the discontinuities in a global coordinate. Some of the cameras might be equipped with GNSS sensor to estimate their world coordinate. However, in most of the cases the GNSS pose estimation might not be accurate enough. Therefore, utilising Visual Simultaneous Localisation and Mapping (VSLAM) fused by GNSS sensors data can be used to accurately estimate the pose of the camera (for example see Kudriashov *et al,* 2020).

The VSLAM technique is mostly utilised in robotics for constructing the map of the area where the robot is mobilised and for determining its own location. In VSLAM, initially distinctive visual features from consecutive images are extract and later by matching them a relative mathematical transformation between them is calculated (denoted as homography). The features are a region on an image with unique shape described by specific vectors that are scale invariant (Szeliski, 2011). VSLAM algorithm can also track those features across several consecutive of images. By estimating the 3D local coordinates of those feature points (using their depth estimated by the stere camera) the relative transformation between two consecutive image frames can be obtained. Subsequently, with utilising these consecutive transformations (which are represented in rotation angles and translation vector), it is possible to obtain the absolute pose of the camera compared to the first frame (the start point of the camera, or camera coordinate system). Fusing the global coordinates of the camera from GNSS sensor and the camera pose in the camera coordinate system will allow us to decrease the uncertainties of the estimated poses of the camera and represent the camera pose in the global coordinate. After that, it will be possible to obtain world coordinate of any pixel point with valid depth using the depth estimated per frame of the 3D movie recorded by the stereo camera.

The challenges in VSLAM arise when such technology is intended to implement in GNSS denied area (like underground mine) where light intensity can also vary. To overcome these challenges, we can fuse the relative poses of the camera from VSLAM with measurements by Inertia Navigation System (INS) which might include an accelerometer, inertial measurement unit, magnetic north sensor, gravity acceleration sensors and barometer (for example see Gao and Zhang, 2021;

Kudriashov *et al,* 2020). In addition, we need to have access to several landmark points (minimum three) around the scene that can be used for transforming the local camera coordinates to a world coordinate. As uncertainties from different sensor measurements should be propagate throughout the entire calculation, factor graph based optimisation of the poses can be a helpful tool (Dellaert and Kaess, 2017).

Detecting and expanding planar patches

The planar patches of a point cloud are detected by Random Sample Consensus (RANSAC) algorithm with some adjustment to better suite our objective (Fischler and Bolles, 1981). The implemented RANSAC algorithm requires following parameters:

- approximate diameter of the smallest visible planar patch at the mapping surface (d_{min})
- planarity ratio (λ)
- agglomeration distance (d)
- angular tolerance (θ).

To implement the RANSAC algorithm, a geologist at the site should make observation and estimate the approximate diameter of the smallest planar element in the mapping surface. The selected diameter allows for finding a small planner sections over the point cloud. Moreover, in the developed software tool, it is possible for the user to select a small area on a frame from the 3D movie captured from the scene, if the automated analysis has not managed to capture it. Moreover, in the developed software tool the user has possibility to select a small area on an image from 3D movie.

Planarity of those patches is controlled via principal component analysis in which the eigenvalues and eigenvectors of the covariance matrix of the 3D points located inside the patches are calculated. For a planar patch, the minimum eigenvalue should be much smaller than both the largest and intermediate eigenvalues. The eigenvector corresponding to the minimum eigenvalue is the normal vector of the planar patch. The ratio of the eigenvalues for planarity check can be expressed as a planarity ratio (λ):

$$\lambda = \max\left(\frac{e_3}{e_1}\ and \frac{e_3}{e_2}\right)$$

Where e_1, e_2 and e_3 are the maximum, intermediate and minimum eigenvalues of the covariance matrix of the points within the boundaries of a patch contained in a sphere with diameter of d_{min}, respectively. The differences of the coplanarity ration between maximum and intermediate eigenvalues should be less than 10 per cent in a planar patch. This ratio is similar to the roughness or waviness of the joint surface, see Figure 2. Our tests on the different rock surfaces show that the best results is achieved when $\Lambda \leq 0.1$. After this step, the algorithm attempts to expand the radius of the planar patch by a ratio of 1–5 per cent of the current radius. The radius of a planar patch is calculated by finding a circumscribed circle that encompasses all points of the patch located on the plane fitted to the patch. If the normal vector of the expanded patch compared to the original patch has angle smaller than the angular tolerance of θ, then the extension of the planar patch is accepted. The process continues until that the expansion of the planar patch radius no longer satisfies the angular tolerance.

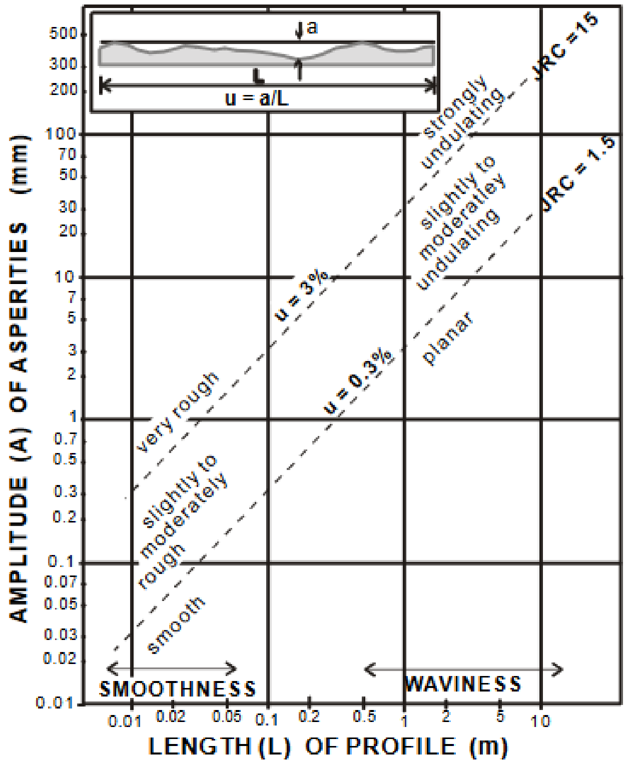

FIG 2 – Rock joint waviness (Palmstrom, 2001).

Mapping discontinuity traces using image processing

To map discontinuities which do not have a visible planar patch in the images, we utilise image processing methods such as edge detection. In the first step, the image transferred to grey scale image, which makes it easy to carry out edge detecting. Then, the image is filtered using Histogram Equaliser Technique (Szeliski, 2011), which is used to remove nonimportant parts of the image and make the intensity of pixels to distribute more uniformly.

Consecutively, after filtering the image, edge detecting algorithm was utilised to find edges in the image. The edges are representing pixels on the images where the intensity of the image pixels changes abruptly. In a simple terminology the edge detector algorithms try to find extrema of the gradient of the image intensity.

Finally, edge pixels which are across from each other, and satisfying the planarity constrains as mentioned before for a planar patch, will be processed. The detected planar patches can be expanded (similar to the planar patches) to include more pixels which are detected as edges by image processing.

Merging coplanar elements

At this stage, all the mapped planar surfaces, whether obtained from the point cloud or through image processing, are presented as planes with a normal vector, centre point and radii. A coplanarity check can be performed across all plane sets with considering by calculating coplanarity angle among them. In this analysis the coplanarity angle threshold is assumed to be slightly larger previous steps. For each set of the combined planes, updated normal vector, centre point and radii will be calculated.

Rock discontinuity network

Eventually, after mapping all visible discontinuity in the scene and storing them as a list of planar circles, it becomes possible to divide them into clusters according to their normal vector orientations. The clustering allows for calculating the best-fitting statistical distributions for each including their orientation (dip and dip-direction), normal spacing and persistence. By utilising Monte Carlo simulation on those previously fitted statistical distribution on the mapping data, user can estimate a statistical distribution of the rock block size in the mapped scene. The detailed mathematical procedure for calculating rock block size distribution is beyond the scope of this manuscript; however, Lu and Latham (1999) provide a comprehensive explanation of those methods.

Example of Implementation

This chapter presents an illustrative example demonstrating the implementation of our developed code for mapping rock mass discontinuities using Zed 2i stereo camera. The study site is a road cut, the fused point cloud from all of the recorded frames from the scene is presented in Figure 3.

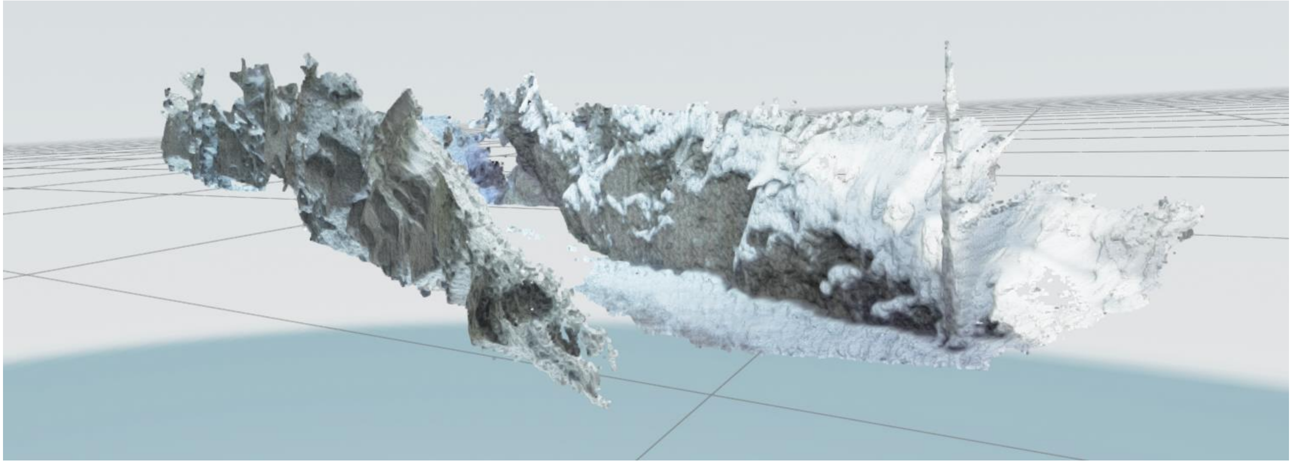

FIG 3 – Fused point cloud from all the frames captured by Zed 2i camera from the study site.

The identifying the planar patches revealed numerous planar surfaces across the exposed rock surfaces Figure 4). However, there are several false positives among detected planes (such as planar surfaces which are covered by snow). Therefore, the code provides the user possibility to reject a certain planar patch, or merge several of them manually. Figure 5 shows the traces of the discontinuities identified in an image from the scene. As it is visible, this process might lead to false positives which again user can approve, reject, or merge them.

The rock block size distribution obtained from rock mass mapping is shown in Figure 6. The analysis reveals that rock blocks at the study site have volumes ranging from 2 to 4.9 m^3. As a rule of thumb when assessing the rock bolt length sufficient to stabilise the slope, the minimum length can be estimated as:

$$l_{bolt} \cong 0.5 + \sqrt[3]{maximum\ estimated\ block\ volume}$$

This calculation can indicate that rock bolt with minimum length of 2.3 m would be appropriate for the study site.

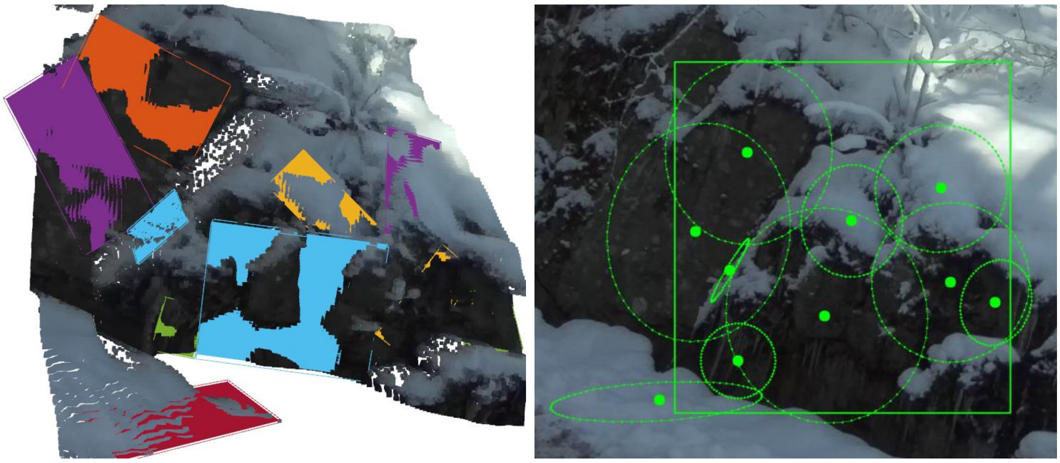

FIG 4 – Mappd planar patches from the point cloud.

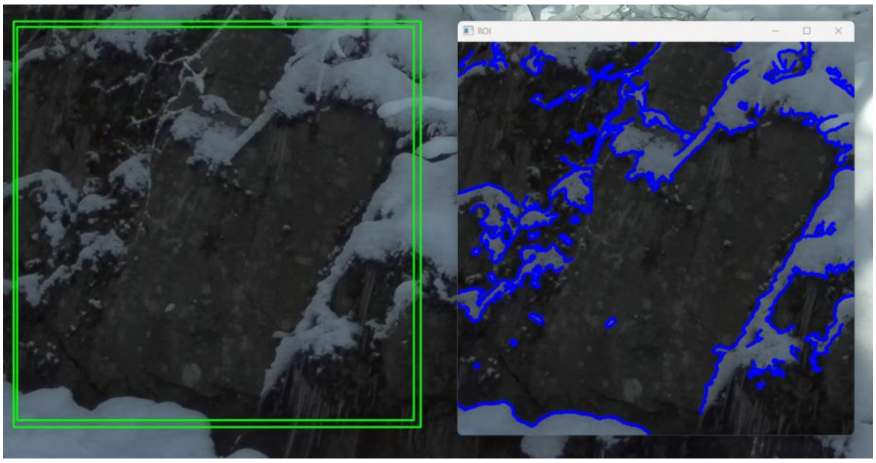

FIG 5 – Mapped traces of the discontinuities.

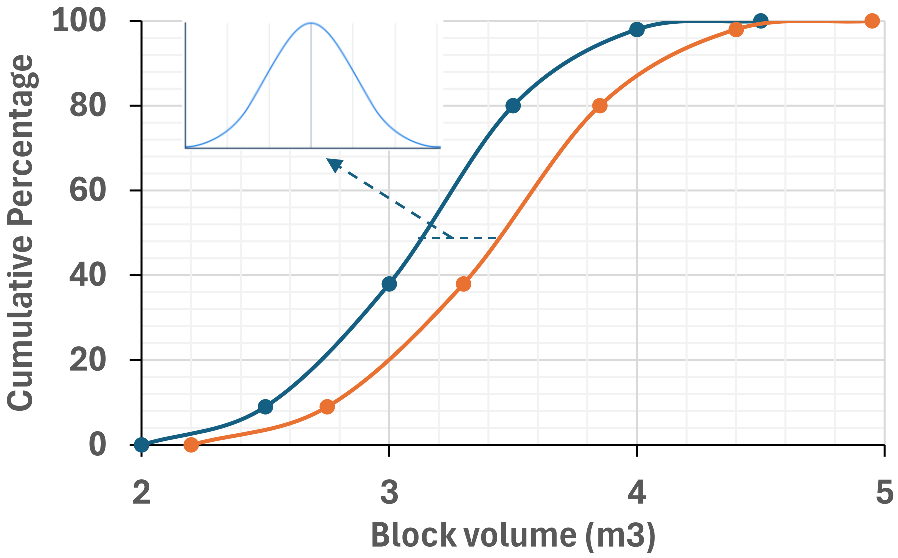

FIG 6 – Estimated distribution of the block sizes at the study site.

CONCLUSIONS

This paper presents a simple and straightforward method for rock mass mapping utilising stereo camera which utilises both the point cloud of the scene and the stored images. The method enables mapping of discontinuities with visible planar patches as well as those without visible planar surfaces in the scene by image processing techniques. In addition, the use of stereo cameras in combination with GNSS sensors or VSLAM allows for simultaneous georeferencing of the mapping results both in the over and underground environments. In addition, the user will have access for manually manipulate the results helping to avoid both false positives and false negatives in the mapping process.

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